

Chapter 5

The Binary Cycles

Today, the term “binary cycle” commonly refers to the organic fluid Rankine engines in geothermal systems, where a mass flow of geothermal brine is cooled in a recovery heat exchanger and the heat recovered is converted into electricity by means of an organic fluid engine (see Chap. 3, Sect. 3.6, and DiPippo [1]).

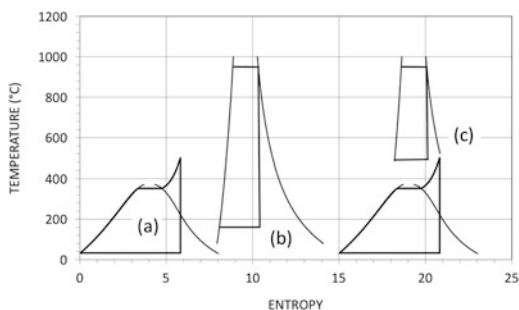
In general, though, the term “binary cycle” can cover any thermodynamic conversion system of heat into electricity with two different fluids involved in the process. In this sense, even the traditional combined gas turbine-steam cycle can be considered a binary system.

Out of the whole region of a general fluid’s existence in the fluid phases, only the region enclosed by the limit curve or closely adjacent to it (see Fig. 4.1), permits the creation of thermodynamic cycles with high-quality thermodynamics¹ like the Rankine cycle with moderate superheating, illustrated by way of example in Fig. 5.1, cycle (a). As discussed in Sect. 1.6, the wide extend of the isothermal transformations, or almost isothermal, and the drastic contraction of the specific volumes following condensation, with a parallel containment of the work of compression, are at the basis of this excellent thermodynamic behaviour. Furthermore, the Rankine steam cycle enjoys an extreme adaptability to fuels and heat sources, but is unable to use heat efficiently at temperatures above 600–650 °C, the excess heat potential being lost as driving force of the heat transmission in the primary exchanger.

Just theoretically, a liquid substance at room temperature and with a critical temperature clearly exceeding the maximum temperatures technically allowed, would permit the creation of near-perfect thermodynamic cycles (see cycle (b) in Fig. 5.1). In reality, though, the exponential relation between the temperature and saturation pressure (see Fig. 2.3a) would quickly make the expansion ratio impractical as the temperature range in the cycle extends excessively, meaning that single-fluid solutions must make way for double or triple fluid solutions (binary or ternary cycles; see cycle (c) in Fig. 5.1).

¹A good indicator of the thermodynamic quality of a cycle is the second-law efficiency, discussed in Exercise 1.2; see (1.22).

Fig. 5.1 (a) Steam cycle.
 (b) A hypothetical Rankine cycle with liquid metal.
 (c) Binary cycle liquid metal steam



To this end, choosing a liquid other than steam would have the purpose of shifting the region of optimum use from the medium to low temperatures permitted by water vapour (below 300–320 °C) to high or very high temperatures (700–900 °C) permitted, for example, by metal vapours.

Thanks to the efforts of William Le Roy Emmet (1859–1941) and the General Electric Company, between 1923 and 1950, resolving tricky technical and technological problems, first there were built several prototypes of turbine and mercury boilers and, subsequently, several mercury and steam binary units.² In the mercury-steam binary cycles, the mercury is heated and vaporised in a mercury boiler and then expanded in a turbine. In a mercury-steam condenser, the exhausted mercury vapours—still at a high temperature during the condensation—heat and cause to evaporate the feedwater from the steam cycle. After the condensation, the liquid mercury returns to the preheater and then the boiler; the steam is then superheated by means of the gases produced by the combustion and originating from the mercury boiler and then sent to the steam turbine.

In 1923, an experimental mercury plant (of 1.8 MW) was built in the Dutch Point station in Connecticut, followed in 1928 by the first commercial cycle with a mercury unit of 10 MW and the steam turbine generator of 12.4 MW, for a total nominal power of 22.4 MW in the South Meadow station (Hartford, Connecticut). Between 1931 and 1933, General Electric built a plant at Schenectady (of 47 MWe) and another at South Kearney, New Jersey, of 45 MWe, both using pulverised coal. In 1949, the Schiller unit began operation, at Portsmouth, New Hampshire, with a total 43.4 MW (two mercury units and one steam unit). In 1949, operation also began at the General Electric power station in Pittsfield, Massachusetts, (of 21.6 MW) and a new unit at South Meadow (of 34.1 MW), [2, 3]. The Schiller unit was shut down in 1968, after 20 years of service.

According to date reported in [3, p. 578], the specific heat consumption of the South Kearney plant (which operated for 110,000 hours) was 14 % lower than that of

²The mercury vapours are extremely toxic, and the mercury does not wet the metal surfaces, creating major problems of heat exchange. The first mercury boilers were subject to tube plugging and failures, with massive corrosion of the tubes, made in low carbon steel, [2]. Water and air infiltration into the mercury circuits created further problems.

the steam power stations with a similar power in those years. The mercury turbine throttle pressures and temperatures in the last plants that came into operation in 1949 were (average values) 8.7 bar and 500 °C, respectively, with the exhaust conditions of about 0.15 bar and 260 °C. The reliability of the mercury vapour turbines (in single and double flow) was excellent. The rotation speed was between 720 and 1,200 rpm.

From 1950, mercury binary cycles were no longer built: the improvement in the operating conditions of steam cycles, their high power and significant economies of scale, as well as the high cost of mercury and the serious corrosion problems it created at high temperatures—never truly resolved—made the binary plants no longer financially viable. However, the study of thermodynamic cycles with liquid metals continued throughout the 1960s, in the United States, with the SNAP (System for Nuclear Auxiliary Power) programme and with the development of mercury units of 30–90 kW, with nuclear heat sources, to be used on space missions with expansion start temperatures of 650–700 °C. In those years, potassium was also considered and studied, and components and turbines were made with operating temperatures of 800 °C. No power plant with potassium has been built, though. In [4, 6] the two detailed projects for potassium-steam binary cycles in the 500–600 MW power range are reported. In [4] the proposal is for a molten salt nuclear fission reactor at high temperature (temperature of the reactor 982 °C, maximum temperature of the potassium cycle equal to 838 °C), with an efficiency of the combined system equal to 54.6%. In [6] the potassium boiler is also the combustion chamber of a gas turbine.

Other organic and inorganic fluids were proposed as working fluids in topping cycles (even sulphur [5]). In [7], as an alternative to the use of mercury, binary cycles are proposed with diphenyl oxide³ and steam. The cycle with diphenyl oxide, superimposed on the cycle with steam, has a maximum temperature of 400 °C. In the opinion of the paper's author the thermal decomposition of diphenyl oxide at 400 °C in normal carbon steel can be ignored. In [8] there is a description of a boiler steam plant with a superheating of the steam obtained from a eutectic mixture of diphenyl and diphenyl oxide at 382 °C and 7 bar. The plant operated for a year.

The metal liquids are suitable for creating high-temperature cycles positioned above a steam cycle. It is possible, though, to make binary cycles with the steam constituting the high-temperature section, as in the first binary cycles proposed, with the aim of preventing steam condensation at excessively low pressures (see [9]). A fairly recent, concrete example of this is the pilot plant described in [10]. An ordinary steam cycle uses the primary heat up to a condensation temperature of around 80 °C (0.5 bar) and releases the waste heat to an ammonia boiler at a pressure of about 35 bar. The ammonia cycle not only replaces the low-pressure section of the steam expander (the biggest, most mechanically stressed and costly) but also allows the power plant's waste heat to transfer, without further intermediary

³A heterocyclic organic compound, also called dibenzofuran, $C_{12}H_8O$. With $T_{cr} = 550.85$ °C, $P_{cr} = 36.34$ bar. With boiling temperature of 285.16 °C and a melting point at 81–85 °C.

circuits, to the dry towers with which the plant is equipped. The thermodynamic loss linked to the heat exchange in the condenser-evaporator is largely compensated by the lower condensation temperature that the system (unlike the ordinary steam system) ensures during the cold seasons. A second example of the use of organic fluid engines in steam power stations is described in [11]. The existing steam plants on the coast could use sea water, collected at a 100 m depth, which (along the Italian coasts) can be found at a perennial temperature of about 13 °C. These current plants are not able to use efficiently the potential of increased power given by using cooling water at low temperatures, because the passage section into the low-pressure elements of the turbine is insufficient. One plant scheme for resolving the problem could be to resort to organic fluid Rankine engines, which use the steam extracted during the expansion in the turbine and the condensate coming from the regenerators. The problems linked to the choice of bottoming cycles with fluids other than steam, on account of the low temperature, are the same as those that characterise the organic fluid Rankine engines, to which Chap. 3 was dedicated.

In Sect. 5.1 we shall discuss the binary cycles with liquid metals, which would permit a simplification of the technological problems connected with the use of materials at excessively high pressures and temperatures, typical of the supercritical steam cycles while, at the same time, significantly improving the conversion efficiency.

5.1 The Binary Liquid Metal–Steam Cycle

As we have said more than once, from a purely thermodynamic point of view, the best performances of a cycle are obtained when the heat is mainly introduced at the maximum operating temperature and the residual heat is rejected back into the environment at the lowest temperature: the saturated Rankine cycles are the practical example of this.

If a cycle is made on the limit curve, like type (b) in Fig. 5.1, the pressures vary exponentially with the temperature, and if the $\tau = T_H/T_C$ ratios are high, the expansion ratios are generally too high and difficult to handle. For example, in a mercury Rankine cycle with $T_C = 300$ K and $T_H = 900$ K ($\tau = 3$), the volumetric expansion ratio is in the order of 3×10^6 , a value that cannot be handled in any real plant. So, the binary cycle with liquid metal and steam in which the waste heat of the unit at high temperature is released to the steam Rankine cycle below could be a solution.

Table 5.1 collects various thermo-physical properties for certain liquid metals of possible interest for use, maybe future, in energy conversion systems.

The low molecular complexity of liquid metals ($\sigma < 0$, Sect. 2.5) and the high critical temperature mean that once the evaporation temperature T_H is fixed, the reduced temperature (T_H/T_{cr}) is low and the contribution of preheating the liquid is small compared to the evaporation heat (see Sect. 2.4 and Fig. 2.3b), resulting in good quality thermodynamics for the Rankine cycle created (see also, for example, cycles (a) and (b) of Figs. 5.1, 1.14b, and 1.15). Regeneration, with the aim of

Table 5.1 Some physical properties of liquid metals for binary (or ternary) cycle applications

Fluid	M ^a	T _{cr} ^b	P _{cr} ^c	MT ^d	T _{vp} ^e	BT ^f
Lithium, Li	6.94	3,527	970	180.5	925.73	1,342
Sodium, Na	22.99	2,300	341	97.8	568.07	883
Magnesium, Mg	24.3	2,262	n.a.	650	764.36	1,107
Potassium, K	39.1	1,900	167	63.5	458.84	759
Rubidium, Ru	85.48	1,833	134	39.3	398.97	688
Cesium, Cs	132.9	1,775	117	28.5	384.72	671
Mercury, Hg	200.6	1,490	1,530	−38.4	195.61	356.7
Lead, Pb	207.2	5,127	n.a.	327.46	1,199.76	1,749
Bismuth, Bi	208.98	4,347	n.a.	271.4	1,094.16	1,564

^aMolecular weight (g/mol)^bCritical temperature (°C)^cCritical pressure (bar)^dMelting temperature (°C)^eSaturation temperature at 0.02 bar (°C)^fBoiling temperature (°C)

reducing the entropic losses in the phase of preheating the liquid, is, therefore, not necessary for cycles with liquid metals.

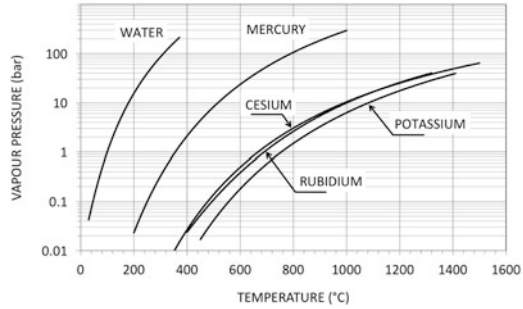
The alkali metals constitute the first group in the periodic table of elements and they are lithium, sodium, potassium, rubidium and caesium. The first group also contains francium (Fr), which is very rare and radioactive (produced from the decay of actinium 227). All the alkali metals are highly reactive and are not to be found in their elementary state in nature, but they are fairly common in the form of compounds (Na \approx 2.8 % in the lithosphere, K \approx 2.6 %, Li \approx 10^{−3} %, Ru \approx 10^{−2} %, Cs \approx 10^{−4} %); sea water contains, on average, around 2.9 % of NaCl and around 0.008 % of KCl and a quantity of 0.01 – 0.04 g/l of rubidium and lithium. There are large deposits of NaCl and KCl, containing small percentages of LiCl, RbCl, and CsCl, originating from the evaporation of ancient inland seas. Sodium and potassium are also present in significant quantities in plants and other living beings.

Magnesium, a metal from the second group of the periodic table of elements, is also highly reactive and not to be found in nature in its elementary form. It constitutes about 2.5 % of the lithosphere. Bismuth, in the fifth group, constitutes about 2 · 10^{−5} % of the lithosphere and is mostly present in the form of sulphur compounds and oxides. Its melting temperature is excessively high (see Table 5.1). Mercury is the only metal in liquid phase at room temperature.

The reactor “clementine”, of 25 kW, the first fast nuclear reactor, designed and built between 1945 and 1946 (reaching full power in 1949), used mercury as its coolant.

Sodium has been used as cooling fluid in fast reactors of the LMFBR (Liquid Metal Fast Breeder Reactors) type. Its high boiling point (see Table 5.1) means that a low pressure can be maintained within the nuclear section of the plant and, at the

Fig. 5.2 Vapour pressure as a function of the temperature for some alkali metals, for mercury and for water



same time, obtain a steam with optimal thermodynamic characteristics (for example, steam at 170 bar and 500 °C). The high heat exchange coefficients allow high power densities (up to 800 kW/l). On the downside and a common characteristic of all liquid metals, if the fluid gets contaminated by impurities (for instance, oxygen and hydrogen), phenomena of steel corrosion can increase dramatically. Sodium, like all alkali metals, reacts violently with oxygen in the air, and if any liquid (in the case of minor leakage) is nebulised in the air, then the reaction is violent. In large quantities, liquid sodium burns slowly on the exposed surface.

Other metals considered during the development phase of fast reactors include potassium, caesium, lithium, and mixtures of sodium-potassium. For the reactors of the so-called Generation IV, there are projects of fast reactors using lead or lead-bismuth eutectic mixtures as coolant.

Excluding mercury, on account of its toxicity and limited production, of the metals listed in Table 5.1, those with the highest vapour pressure are caesium, rubidium, and potassium. Figure 5.2 shows the vapour pressure curves for caesium, rubidium, and potassium and, for comparison, mercury and water. Caesium and rubidium have very similar vapour pressures; Caesium has a molar mass 1.55 times greater than rubidium, which implies smaller enthalpy drops in the turbine and less evaporation heat (therefore, tending to a higher mass flow rate for the same useful power), and higher vapor density at the same temperature and pressure. Rubidium is much more abundant than caesium, in fact, similar to zinc. Potassium, among the three alkali metals considered, has the lowest molar mass, is widely available and at low cost, but, at the same temperature, has a lower vapour pressure than rubidium: for example, at the temperature of 500 °C, the vapour pressure of potassium is 0.042 bar, but that of rubidium is 0.11 bar. The useful power (at preset dimensions and fixed condensation temperature) on a single exhaust flow turbine therefore tends to be lower than that for caesium or rubidium.⁴

⁴The power \dot{W} of the last stage of a turbine is, approximately, if calculating on a preset number of Mach, like $\dot{W} = \dot{m} \Delta H \propto \rho D^2 v_s v_s^2 \propto (P/T) M D^2 v_s^3 \propto D^2 (P/T) M (T/M)^{3/2}$, with D average diameter, ρ density of vapour, v_s speed of sound, ΔH enthalpy drop and M molecular weight. For the same average diameter and the same condensation temperature, the power is, therefore, approximately proportional to the ratio P/\sqrt{M} . For example, assuming $T = 500$ °C,

All the alkali metals are highly reactive, with the risk of fire, so air (and all compounds in general that contain oxygen, including water) must absolutely not be used in the circuits. In the case of potassium, for example, corrosion, too, increases dramatically in the presence of an oxygen concentration of just a few parts per million [2].

A broad discussion of the problems of corrosion for alkali metal, liquid, and vapour on structural materials and the problems of corrosion for combustion products can be found in [12]. Potassium at 870 °C seems less corrosive than steam in the presence of Ni – Cr alloys. The refractory metals do not manifest any corrosion with potassium up to 1,000 °C, but they cannot be used in combustion systems, given their high reactivity to oxygen. The maximum pressures in a cycle with alkali metals are hundred times lower than those in the USC steam cycles and the stress in the potassium tubes, for example, is very low: the austenitic steels seem adequate for potassium up to temperatures of 850–900 °C. One possibility for alleviating the problems of corrosion linked with the use of carbon with a high presence of sulphur could be the adoption of a pressurised fluidised bed combustor, in which a sorbent (limestone or dolomite), mixed with the carbon, traps the sulphur, reducing the corrosive action of the combustion gases [13, 14].

As far as potassium is concerned, 800,000 hours of testing have been accumulated, with operating temperatures even greater than 540 °C: in turbines with two or three stages at 815 °C, in boilers in the range 760–1,200 °C, in condensers at 600–870 °C, in mechanical and electromagnetic pumps and in throttle and shut-off valves [2]. In conclusion, a firm technological base exists for potassium Rankine systems, albeit for smaller components than those used in a large power station. However, a pilot plant has never been built.

Without doubt, planning and building systems with alkali liquid metals as the working fluids presents many difficulties. The characteristics of liquid metals, though, are unique (also in terms of conductivity and viscosity) and developing the technology in this sector could bring numerous benefits.

When a number N of thermodynamic cycles are superimposed, assuming that all the waste heat from a cycle is completely used and constitutes a unique heat source for the lower contiguous cycle, the efficiency η of the multiple cycle is a function of the efficiencies of the individual cycles that compose it, according to (see [12])

$$\eta = \eta_1 + \sum_{i=2}^N \eta_i \prod_{j=1}^{i-1} (1 - \eta_j) \quad (5.1)$$

with index 1 identifying the cycle with the highest temperature. In the case of a binary cycle, made by superimposing two cycles 1 and 2, (5.1) becomes

the power of the stage with rubidium would be approximately 1.7–1.8 times greater than that of the stage with potassium.

$$\eta = \eta_1 + \eta_2 (1 - \eta_1) \quad (5.2)$$

In the case of a ternary cycle,

$$\eta = \eta_1 + \eta_2 (1 - \eta_1) + \eta_3 (1 - \eta_1) (1 - \eta_2) \quad (5.3)$$

The various terms $(1 - \eta_j)$ take into account the fact that the thermal energy available for each cycle diminishes, passing from the upper to the lower thermodynamic cycle, because part of it is gradually converted into work.

5.2 The Binary Potassium and Rubidium–Steam Cycle

The most obvious solution in designing a binary liquid metal–steam cycle is that of condensing the metal vapours at a temperature just slightly higher than the maximum temperature of a steam cycle, according to the scheme in Fig. 5.3a. However, in the configuration shown in Fig. 5.3a, there is a great irreversibility of heat exchange between the metal vapours that condense and the vapour that preheats, evaporates, and superheats (an irreversibility due to the great difference between the condensation temperature of the metal cycle and the evaporation temperature of the steam). A more efficient solution from a thermodynamic point of view is shown in Fig. 5.3b, with two levels of condensation for the metal cycle. Multilevel condensation is thermodynamically advantageous, just like multilevel evaporation, which is typical of combined cycles with gas turbines and steam. Figure 5.3b, reports the total entropy and not the specific entropy for the expanding metal vapour: the entropy of the diagram is the sum of the entropy of the fluid that continues the expansion and the entropy of the vapour that condenses.

As a further example, a configuration like that of Fig. 5.4 (with the metal cycle at a maximum temperature equal to that of the steam cycle) would allow a significant reduction of the irreversibilities (that is, the thermodynamic imperfections) typical of the steam cycle: an average temperature of heat introduction originating from the primary energy source, which is far lower than the maximum temperature of the cycle. In Fig. 5.4, the condensation of the metal vapours at low temperature brings about the evaporation of the steam (from point 1 to point 2), and the condensation at a higher temperature is responsible for superheating the steam up to the temperatures (to be optimised) corresponding to points 3 and 5. Obviously, the final superheating and resuperheating must occur (in the scheme of Fig. 5.4) using thermal energy originating from the outside (sections from 3 to 6 and from 5 to 7) and (5.2) is not applicable. The overall efficiency is significantly increased, however. For instance (see [15]), it becomes 52 % with the steam cycle efficiency at 0.43 and the potassium topping cycle efficiency at 0.18 (maximum temperature 600 °C, minimum temperature 40 °C). In the examples illustrated in Figs. 5.3 and 5.4, the cycles shown are purely indicative.

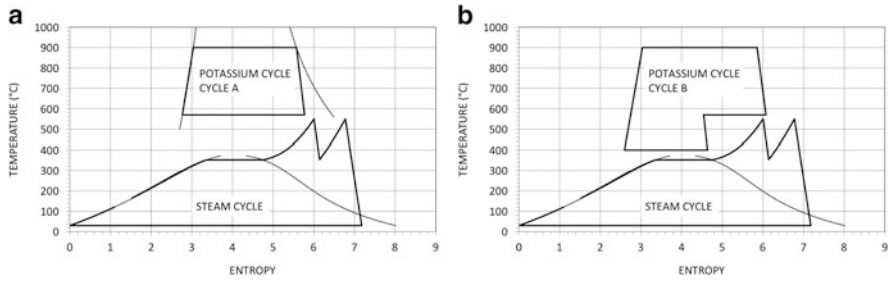


Fig. 5.3 Binary cycles with liquid metal and steam. (a) Metal cycle with single level of condensation, (b) Metal cycle with two levels of condensation

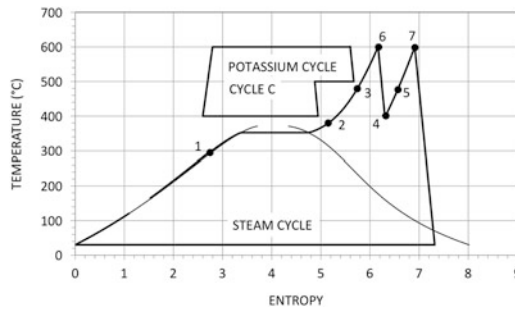


Fig. 5.4 Thermodynamic scheme of a topping cycle with liquid metal, with maximum temperature the same as the steam cycle

Referring to the drawings in Fig. 5.3, assuming a prefixed value (hereafter, 20 °C) of the pinch point temperature difference in the condenser of the liquid metal cycle and fixing a maximum temperature for the cycle with metal, the resulting binary cycle has an efficiency that depends on the maximum temperature of the steam cycle. In the case of a cycle with just one level of condensation (cycle A in Fig. 5.3a) Fig. 5.5a reports, for potassium and rubidium, the thermodynamic efficiency of the metal cycle as the maximum temperature varies, assuming a minimum temperature of 570 °C. The efficiencies are substantially the same (equal to about 0.19 when the maximum temperature is 850 °C). The main differences between the two metals lie in the different molar mass (39.1 for potassium, 85.48 for rubidium) and (having set the temperature) in the greater vapour pressure of rubidium with respect to potassium (for example, see Fig. 5.2, at 570 °C, 0.12 bar for potassium and 0.27 bar for rubidium). The greater molar mass reduces the work of expansion and the speed of sound, profoundly affecting the turbine design, and the greater vapour pressure, once the power is set, reduces the volume flows and the dimensions of the tubes and the turbine. Figure 5.5b compares (for cycle A) the metal vapour volumetric flow rates per MW of useful power of the metal cycle in the case of rubidium and potassium: the volume flows of potassium are almost double than those of rubidium.

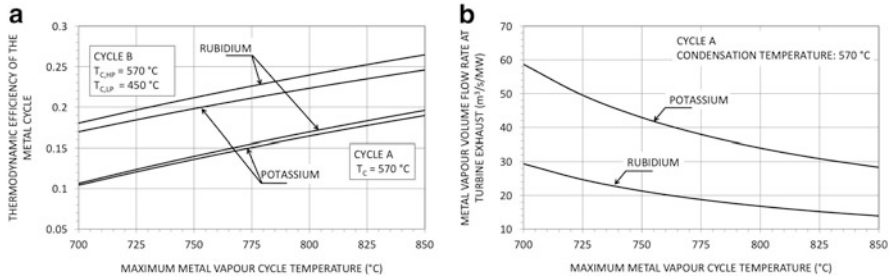


Fig. 5.5 (a) Efficiency of cycles with liquid metal with one and two levels of condensation as a function of maximum temperature. (b) Volume flows at the outlet of the turbine as maximum temperature varies per MW of useful power, in the case of a metal cycle with just one level of condensation

The efficiency of the binary cycle depends on the efficiency of the steam bottoming cycle and can be calculated using the relation (5.2), assuming η_1 is equal to the efficiency of the metal cycle and η_2 is equal to the efficiency of the steam cycle.

Assuming the steam bottoming cycle depicted in Figs. 1.25 and 1.29, with the basic assumptions for the calculations for Table 1.4 and a thermodynamic efficiency of 0.465 (see Exercise 1.7), we obtain, for a metal vapour cycle temperature of 850°C (see Fig. 5.5a), an $\eta = 0.19 + 0.465(1 - 0.19) = 0.57$.

In general, once the maximum temperature of the metal cycle is set, there is a strict dependence of the efficiency η on the maximum temperature of the steam cycle. In the case of cycle A, an increase in the maximum temperature of the steam cycle reduces the η_1 efficiency and the efficiency η of the binary cycle tends to diminish with the increase in the maximum temperature of the steam cycle (even though, clearly, it will always be superior to the η_2 value of just the steam cycle). This occurs because of the rapid deterioration in the efficiency of the metal cycle as the condensation temperature rises, compared to the increase in efficiency of the steam cycle as the maximum temperature rises.

Figure 5.5a also represents the efficiency of potassium and rubidium cycles with two levels of condensation (at 570°C and at 450°C , cycle B of Fig. 5.3b), as the maximum temperature of the metal cycle varies. Condensation with two levels benefits significantly the thermodynamic performance of the cycle (for example, at the maximum temperature of 850°C , in the case of potassium, the efficiency passes from 0.189 to 0.246). By contrast, the condensation pressures at the lower temperature diminish rapidly, with problems for the dimensions of the final stages of the turbine: in the case of potassium, for example, if the LP condensation temperature passes from 500°C to 400°C , the efficiency of the metal cycle passes from 0.225 to 0.261 (with a maximum temperature of 850°C and an HP condensation temperature of 570°C), but the volume flow at the outlet of the power unit increases from $280.8\text{ m}^3/\text{s/MW}$ to $612.6\text{ m}^3/\text{s/MW}$.

In the case of cycle B of Fig. 5.3b, as the maximum temperature of the steam cycle rises (once the maximum temperature of the metal cycle is set), unlike the case with cycle A, there exists an optimal value for the efficiency of the binary cycle, although not particularly pronounced; see [12].

Topping Cycle Turbine Design

In principle, designing turbines with metal vapours is not much more complicated than for the large steam turbines. The overall pressure ratio of the steam cycle in Fig. 1.29, for example, is equal to 4,000, for a cycle with potassium or rubidium, between 850 °C and 400 °C, though, it is 372 and 161, respectively. The specific work of the metal vapours is significantly inferior to that of steam: a typical cycle among those considered produces 500–250 kJ/kg and 200–100 kJ/kg for potassium and rubidium, respectively. These compare with values of 1,000–1,500 kJ/kg in the case of typical steam cycles.

Only with regard to vapour quality during expansion are the cycles with metal vapours critical (typically, for the cases we have considered, the vapour quality is 0.74–0.77, at the end of expansion). A similar situation can be found in traditional nuclear steam cycles, and the problem can be tackled by resorting to adequate fluid dynamics design and to extraction devices similar to those adopted in steam cycles [16–18].

As an example of the dimensions in designing a turbine with metal vapours, with reference to cycle B of Fig. 5.3b, having set an acceptable maximum dimension for the final stage,⁵ it is possible, for each working fluid, having identified the condensation temperature $T_{C,LP}$, to evaluate the corresponding vapour flows. An eight-stage configuration has been assumed for the turbine (with two LP flows and three stages for each flow and five stages for the expansion at high pressure) in such a way that all the stages are subsonic. As another calculation hypothesis, the kinetic energy at the outlet of each stage is kept at 3–4 % of the enthalpy drop.

The temperature $T_{C,HP}$ is fixed at 570 °C, the $T_{C,LP}$ at 450 °C, the maximum temperature $T_E = 850$ °C and the bottoming steam cycle of reference is that in Figs. 1.25 and 1.29 (see also Exercise 1.7).

Several results for the turbine with potassium (the fluid at the lowest condensation pressures, having fixed the temperatures $T_{C,HP}$ and $T_{C,LP}$), and rubidium as working fluids are shown in Tables 5.2 and 5.3. For the turbine with potassium, the number of revs is set at 1,500 rpm, and the tip diameter of the final stage at low pressure is 5.4 m (see Table 5.2), with a h/D ratio of 0.277. The volume flows between the first and last stage vary between 74 and 1,461 m³/s.

⁵In the case of steam turbines, stages have been designed with a tip diameter of 4.32 m at 3,000 rpm and stages with a tip diameter of 6.7 m at 1,500 rpm with h/D ratios, height of blade with respect to average diameter, of 0.39 and 0.37, respectively.

Table 5.2 Some characteristics of the double-flow LP turbine for potassium and rubidium

LP turbine — Two flows — Three stages			Potassium	Rubidium
Number of revolution			1,500 rpm	750 rpm
Overall pressure ratio			7.14	5.14
Overall isentropic work			307 kJ/kg	75 kJ/kg
Isentropic power per stage			1,843 kW	2,116 kW
First stage	Tip diameter		4.38 m	4.38 m
	Mean diameter		4.01 m	3.95 m
	h/D^a		0.0926	0.11
	Reaction degree at mean radius		0.5	0.5
	Volume flow ratio		1.67	1.49
	Exhaust volume flow		446 m ³ /s	247 m ³ /s
Second stage	Tip diameter		4.65 m	4.62 m
	Mean diameter		4.01 m	3.95 m
	h/D^a		0.161	0.173
	Reaction degree at mean radius		0.5	0.5
	Volume flow ratio		1.76	1.59
	Exhaust volume flow		784 m ³ /s	392 m ³ /s
Third stage	Tip diameter		5.40 m	5.27 m
	Mean diameter		4.22 m	4.16 m
	h/D^a		0.277	0.266
	Reaction degree at mean radius		0.55	0.55
	Volume flow ratio		1.87	1.66
	Exhaust volume flow		1461 m ³ /s	651 m ³ /s

^a Mean blade high to mean diameter ratio

In the case of rubidium, the LP section is chosen with geometric dimensions that are approximately the same as those of the turbine with potassium and the 750 rpm represents the closest synchronous velocity to that which guarantees a specific number ω_s at each stage, close to those of the stages with potassium.

The tip peripheral velocities of the turbine stages with rubidium are around half those of potassium: 125–207 m/s, from the first to the last stage, compared to 240–424 m/s. The turbine power with potassium is 36.8 MW and with rubidium is 43.6 MW.

Some Concluding Remarks

Analysis and discussion have shown how there already exist materials that are capable of enabling the use of alkali metals in power cycles superimposed on standard steam cycles, with global thermodynamic efficiencies of 55–60% and relatively modest maximum temperatures (750–850 °C) and evaporation pressures for the metal section of just a few bar (3.8 bar, for rubidium at 850 °C). The specific

Table 5.3 Some characteristics of the HP section of turbines with potassium and rubidium

HP turbine — Single flow — Five stages		Potassium	Rubidium
Number of revolution		1,500 rpm	750 rpm
Overall pressure ratio		18.6	14.1
Overall isentropic work		519 kJ/kg	134 kJ/kg
Isentropic power per stage		5,148 kW	6,172 kW
First stage	Tip diameter	3.02 m	3.17 m
	Mean diameter	2.93 m	3.05 m
	h/D^a	0.029	0.04
	Reaction degree at mean radius	0.06	0.1
	Volume flow ratio	1.5	1.4
	Exhaust volume flow	73.8 m ³ /s	54.8 m ³ /s
Last stage	Tip diameter	4.14 m	4.39 m
	Mean diameter	3.52 m	3.68 m
	h/D^a	0.176	0.192
	Reaction degree at mean radius	0.35	0.38
	Volume flow ratio	1.82	1.7
	Exhaust volume flow	582 m ³ /s	344 m ³ /s

^a Mean blade high to mean diameter ratio

isentropic work, far inferior to that of steam, means that just a few turbine stages need to be used and these are not particularly stressed from a mechanical point of view.

In the ordinary steam cycles, a rise in the maximum temperature up to 700–800 °C would not raise efficiency to those levels obtained with a binary cycle, due to the fact that the average temperature of heat introduction is significantly lower than the maximum temperature.

On the other hand, condensation pressures in the metal cycle tend to be very low, which leads to very large volume flows at turbine exhaust, with serious fluid dynamic problems that limit the maximum power obtainable, making it very difficult, in practice, to build large-scale plants

In any case, even though this particular technology has interesting thermodynamic possibilities, there is no specific research activity taking place at present in the sector of binary cycles with liquid metals.

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